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SUMMARY

High-pressure turbopumps for advanced reusable liquid-propellant rocket engines such as that for the Space Shuttle Main Engine (SSME) require turbine blade materials that operate under extreme conditions of temperature, hydrogen environment, high-cycle fatigue loading, thermal fatigue and thermal shock. Such requirements tax the capabilities of current blade materials. Based on projections of properties for tungsten fiber reinforced superalloy (FRS) composites, it was concluded that FRS turbine blades offer the potential of a several fold increase in life and over a 200 °C increase in temperature capability over the current SSME blade material. FRS composites were evaluated with respect to mechanical property requirements for SSME blade applications. Compared to the current blade material, the thermal shock resistance of FRS materials is excelient, two to nine times better, and their thermal fatigue resistance is equal to or higher than the current blade material. FRS materials had excellent low and high-cycle fatigue strengths, and thermal shock-induced surface microcracks had no influence on their fatigue strength. The material also exhibited negligible embrittlement when exposed to a hydrogen environment.

INTRODUCTION

The need for improved performance and longer life in advanced liquid propellant rocket engines has stimulated interest in the potential benefits of advanced high-temperature structural materials for rocket engine turbopump turbine blades. Historically, the rocket engine industry has relied on aircraft gas turbine materials, however, there are significant differences in the requirements placed on blade materials in rocket engine turbines compared to aircraft gas turbines, as shown in Table I. It has become apparent that the blade materials developed by the aircraft gas turbine industry do not necessarily meet some of the operating requirements of liquid propellant rocket engines, such as very severe thermal start/stop transients, high operating speeds, and hydrogen environments. These conditions result in unique requirements including: high thermal strain low-cycle fatigue strength; high mean stress high-cycle fatigue strength; resistance to hydrogen environment embrittlement; thermal shock resistance; and relatively short time stress-rupture/creep strength.

Currently the most advanced large, liquid propellant rocket engine in service is the Space Shuttle Main Engine (SSME) and it utilizes directionally solidified hafnium-modified MAR M246 (MAR M-246 (Hf) (DS)) for the high pressure fuel turbopump and the high pressure oxidizer turbopump turbine blades. In this instance the fatigue requirements on the alloy are particularly severe as evidenced by the fact that the MAR M-246 (Hf) (DS) turbine blades in both turbopumps are subjected to life-limiting fatigue cracking. There is thus a need to improve turbine blade materials for increased life under current SSME operating conditions and to increase the temperature capability for future rocket engines.

A study was conducted to identify those materials that would provide the greatest benefits as a turbine blade material for advanced liquid propellant rocket engine turbines, Ref. 1. The candidate materials were selected from six classes of materials: fiber reinforced superalloys (FRS), single crystal superalloys (SC), oxide dispersion strengthened superalloys (ODS), rapid solidified processed superalloys (RSP), directionally solidified superalloys (DSE), and ceramics. Mechanical and physical properties were compiled and evaluated, and improvements were projected approximately 5 years into the future for advanced versions of the materials. The estimated values were used in a turbine blade structural analysis based on the design and operating conditions of the SSME and the configuration and operating conditions of the SSME high pressure fuel turbopump first-stage turbine blade where the temperatures of interest ranged from 870 °C, the approximate steady-state operating temperature of turbine blades in the SSME, to approximately 1100 °C. Based on these calculations, development plans were prepared, and benefit analyses were performed to permit the identification of those materials offering the best balance in terms of gains to the system, risk, and development costs. It was concluded that the materials which warranted development were the single crystal superalloys for use at 870 °C, the FRS composite for use at 870 and 1100 °C, and the ceramics for use at 1100 °C. At 1100 °C the FRS composite stood out as being the only one of five metallic classes of materials studied to have the properties to provide adequate rocket engine turbine blade life and was regarded as the leading candidate for this application.

Fiber reinforcement of superalloys has a long history and is a relatively mature technology. Tungsten fiber reinforced superalloy composites have been of interest for air breathing gas turbine blade application for more than 20 years in the United States, Great Britain, Sweden, and the USSR due to their (1) potential use temperature advantage of over 160 °C above that of conventional superalloy blade materials and (2) capability to provide longer operating life. Work on FRS in the United States has been most actively pursued by NASA Lewis Research Center where emphasis has been on evaluating tungsten fiber reinforced FeCrAlY, Refs. 2 and 3. The feasibility of

fabricating complex shaped blades of FRS composite material has been demonstrated, Ref. 4. A cooled aircraft gas turbine blade that was fabricated as a result of this program is shown in Fig. 1. A comprehensive review of the status of FRS composite materials can be found in Ref. 5.

Both in-house and contractual studies (Refs. 6 to 8) are being conducted to evaluate the use of fiber reinforced superalloys for rocket engine turbopump turbine blades. The first-stage blades of the high pressure fuel turbopump of the SSME were chosen as the reference system and a preliminary analysis was undertaken based on the use of high strength tungsten alloy fibers in a ductile superalloy matrix. This analysis included modeling to estimate mechanical and physical properties as well as experimental measurements of critical properties. For purposes of comparison to existing technology, estimated and measured behavior of the FRS composite is contrasted with that determined for MAR M-246 (Hf) (DS) at 870 °C. Additionally the properties of fiber strengthened alloys are projected for use at 1100 °C in advanced rocket engines.

ANALYSIS

Materials

Due to their combination of high-strength, high temperature capability and good ductility, tungsten alloy fibers have been favored as the reinforcement for FRS composites. Because the current SSME blades experience a high tensile stress due to a combination of high centrifugal forces and gas bending loads, a high value of specific strength (strength/density) is desirable. Thus the strongest tungsten wire that has been fabricated to date is the W-4Re-0.38Hf-0.02C (weight percent), Ref. 9, which was selected as the reinforcing fiber to be used in the analysis.

The consideration for selection of the matrix material to be reinforced included:

(1) Compatibility with the environment; hydrogen and/or hydrogen/steam
(2) Compatibility with the tungsten alloy fiber
(3) Thermal fatigue resistance
(4) High-cycle fatigue behavior
(5) High tensile ductility

Based on these criteria three iron base alloys (Incoloy 903, FeCrAlY, and 316L stainless steel) and the nickel base superalloy, Waspaloy had potential as matrix alloys. The chemical composition of the matrix materials are shown in Table II. These materials are different in many respects and each has attractive features for use a matrix material. Waspaloy is representative of a ductile nickel base superalloy that maintains high tensile strength up to 870 °C. Incoloy 903 (IN 903) is one of several austenitic iron alloys (IN 903, 905, 907, 909) developed by INCO for low thermal expansion properties and is resistant to hydrogen environment embrittlement. The commercial 316L austenitic stainless steel is also resistant to hydrogen environment embrittlement. Finally, the FeCrAlY and FeCrAl alloys have been shown to have excellent compatibility with tungsten alloy fibers and tungsten fiber reinforced FeCrAlY has also been shown to have very good thermal fatigue resistance properties.

The FRS system projected for the advanced version of the SSME turbine blade was a composite comprising 50 vol % of W-4Re-0.38Hf-0.02C fibers embedded in a ductile matrix of the compositions indicated previously. Unfortunately experimental property data for these composite systems are limited; therefore, it was necessary to estimate behavior from data and predictive techniques developed under previous metal-matrix composite programs.

Mechanical Properties

Figures 2 and 3 show projections of tensile and specific tensile strengths of candidate FRS composite systems based upon incorporation of W-Re-Hf-C fibers in various matrix alloys. In all cases the composites have an advantage in tensile strength (Fig. 2) over the MAR M-246 (Hf) (DS); however, if specific strength is the critical criteria improvement below 870 °C depends on the matrix alloy (Fig. 3). In terms of expected long term life at elevated temperature, stress rupture projections (Fig. 4) indicate at least a 100 percent advantage in load bearing ability for the FRS system over the conventional superalloy.

The projected high-cycle fatigue behavior of W-Re-Hf-C/Waspaloy composite is contrasted with that of the current SSME blade alloy in Fig. 5. For similar test conditions, the high-cycle fatigue life of the FRS composite is estimated to be three orders of magnitude higher than that for MAR M-246 (Hf) (DS) at 870 °C. Using available fatigue data for FRS composites, Ref. 10, a Goodman diagram has been calculated (Fig. 6) which shows the projected fatigue behavior of W-Re-Hf-C/Waspaloy composites as a function of combined axial and flexural stresses for a fatigue life of 10^8 cycles at 870 and 1100 °C. Additionally the calculated stress at the root of the FRS airfoil designed for this application is also shown in Fig. 6. These data indicate that fiber reinforcement can offer a potential of over 200 °C increase in use temperature.

Although very little strain-controlled, low-cycle fatigue data have been generated for FRS composites, an attempt has been made to estimate a range of low cycle fatigue behavior using the Manson-Coffin approach Ref. 6, and the results for 50 volume fraction content W-Re-Hf-C fibers in a Waspaloy matrix for 870 °C are shown in Fig. 7.

Clearly the low-cycle fatigue behavior for the FRS composite falls within the range obtained for the current SSME blade alloy material.

Blade Redesign

A major feature of the investigation of Ref. 6 involved preliminary design of turbine blades fabricated from advanced materials for the SSME. Because of the high strengths of FRS structures, it was found that the SSME airfoil could be redesigned from the current solid airfoil to a hollow thin-wall member, thereby reducing the mass of the turbine blade. This feature, combined with the relatively high thermal conductivity of FRS composites (Fig. 8), which is approximately double that of MAR M-246 (Hf) (DS) at 870 °C, is a distinct advantage in reducing the thermal strains that accompany engine start and shutdown transients.

VERIFICATION OF FRS PROPERTIES

The results of the turbine blade structural analysis showed that FRS composites have a highly attractive combination of properties for advanced rocket engine turbopump turbine blade applications. In order to develop the FRS composite for use as advanced rocket engine turbine blades however, development of a data base is needed with particular attention to areas such as thermal fatigue, thermal shock and hydrogen environmental embrittlement effects. The first priority was therefore to produce an adequate supply of FRS materials and to measure the key design properties of those materials. Thus a program (Ref. 7) was conducted to evaluate four candidate fiber reinforced superalloy composite systems with respect to mechanical properties required for SSME blade application. The tests included: tensile, ductile-brittle transition temperature determination; thermal shock under SSME start transient conditions; thermal fatigue; low and high-cycle fatigue; and hydrogen environmental embrittlement.

Materials

As the high strength W-Re-Hf-C fiber was not commercially available, a weaker tungsten-1.5 percent thorium oxide fiber was substituted since it is the strongest readily available tungsten alloy fiber. Following the general recommendations of Ref. 6, Waspaloy, 316L stainless steel, Incoloy 907, and FeCrAl (Table II) were utilized as the matrix materials.

For ease of fabrication, FRS composites containing 40 vol % fiber contents rather than 50 vol % were fabricated using an arc-spray process (Ref. 11) to produce monofilament tapes. These were subsequently hot pressed into composite panels 50 mm wide, 150 mm long and 1.5 mm thick with the fiber's length parallel to the panel length. The microstructure of a typical FRS composite is shown in Fig. 9. It is evident that the fibers are evenly distributed within the matrix (Fig. 9(a)) and that there is little evidence of a deleterious reaction between the two components, (Fig. 9(b)). To provide a basis for comparison for the FRS composites in the thermal shock and thermal fatigue tests, MAR M-246 (Hf) (DS) and Alloy 1480 (single crystal) panels were also fabricated. The nominal compositions for MAR M-246 (Hf) (DS) and Alloy 1480 are shown in Table II.

Due to the use of a lower volume fraction, lower strength fiber, mechanical and physical properties of the tungsten-1.5 percent thoria reinforced composites were projected utilizing the same methodology developed for the W-Re-Hf-C strengthened materials. Comparisons of these estimated values to the measured property data were made to assess the potential of FRS composites for use as SSME turbine blades and to assess the validity of projection methodology.

Tensile Testing

Tensile test were conducted using flat sheet specimens fabricated from composite panels by wirecut electro discharge machining. The specimens had a 12 mm gauge length with fibers oriented parallel to the longitudinal axis of the specimens. Tensile tests were undertaken at -196°, 20°, 870°, and 1100 °C and the ductile-brittle transition temperature was estimated from the reduction in area data. Results for the 870 °C ultimate tensile strengths are presented for three FRS composite systems in Table III. The measured values for the 40 vol % tungsten-1.5 percent thoria reinforced materials compare well with the estimated strengths; hence it is concluded that the methodology for projecting tensile strengths is valid and that the ultimate tensile strengths of the W-Re-Hf-C reinforced composites should thus also be equal or higher than the estimates given in Table III.

As temperatures can drop to the cryogenic range during engine shut down in liquid propellant rocket engines based on oxygen/hydrogen fuels, the ductile/brittle transition temperatures (DBTT) for the composite is of interest. None of the three composite systems examined (Waspaloy, 316L stainless steel, and IN 907 matrices) exhibited a ductile-brittle transition temperature from -196 to 1100 °C which is consistant with the matrix alloys. Reduction in area values for the composites range from 5 to 17 percent at -196 °C and 9 to 20 percent at 1100 °C.

Thermal Shock Testing

Figure 10 illustrates the high-pressure fuel turbine inlet gas temperature transients that produce the thermal transient in the turbopump turbine blades of the SSME. Two high-intensity spikes occur within 2 sec of start-up and yield severe thermal shock

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loadings. After this initial period there is a gradual rise in temperature which leads to thermal fatigue damage. In order to simulate these thermal shock transients, a programed computer-controlled, high-intensity electron beam was utilized to repeatedly heat a square area centrally located on polished FRS and superalloy test panels (Fig. 11). A typical time-temperature profile is shown in Fig. 12; in general the maximum temperature ranged from 370 to 980 °C during each thermal shock cycle. The panels were heated from 90 to 870 °C within 0.3 sec.

The number of thermal cycles required to generate surface microcracking for the FRS composites and superalloys are shown in Fig. 13. The FRS composites have excellent thermal shock resistance compared to the present SSME material MAR M-246 (Hf) (DS), which cracked after 1 to 6 cycles, while the single crystal Alloy 1480 was better than MAR M-246 (Hf) (DS), microcracks were still observed after 6 to 11 cycles. In contrast to the unreinforced materials, the worst composite life was 20 cycles (Waspaloy, 316L stainless steel and FeCrAl matrices) while the IN 907 composite resisted over 45 cycles before any signs of microcracks were observed. The thermal shock damage in the FRS composites and superalloys occurred primarily in the surface of the panels. The superior thermal conductivities of the FRS composites readily dissipated the heat generated by the thermal shock cycles. This minimized the temperature gradient and consequently the thermal strains were less severe in the FRS composites than in the superalloy panels. A significant improvement in thermal shock resistance can thus be gained using this class of materials for rocket engine turbine blades.

Thermal fatigue Testing

In order to simulate the thermal transients that occur after 2 sec of SSME engine start-up which leads to blade thermal fatigue damage, a programed computer-controlled high-intensity electron beam was utilized to heat polished test panels. A thermal analysis of the SSME airfoil indicated that the average heating rate for the airfoil occurring from 2 to 5 sec after engine start was about 220 °C/sec. To produce the same heating rate in the FRS composite test panels as in similar panels machined from superalloys, the power input into the FRS composites had to be increased because of their higher thermal conductivity: for example the 870 °C peak temperature tests required 66 percent more power to produce the desired heating rate in the FRS composite panels as compared to the superalloys, while the 1100 °C peak temperature tests required 38 percent more power. All panels were cycled 55 times before the thermal fatigue tests were terminated. The test results for the thermal fatigue experiments are given in Table IV. In the 870 °C tests, the unreinforced superalloys performed well and in some cases better than a few of the composites. The single crystal Alloy 1480 and the tungsten/Waspaloy composite showed no indications of microcrack initiation after 55 thermal fatigue cycles. The MAR M-246 (Hf) (DS) and the tungsten/316L stainless steel composite had microcracks after 45 to 55 thermal fatigue cycles, and the tungsten/Incoloy 907 and tungsten/FeCrAl composites developed microcracks between 11 and 31 thermal fatigue cycles. At the 1100 °C peak temperature all of the materials showed indications of microcracking before the desired 55 cycles were achieved. At this maximum temperature the best performing material was tungsten/316L stainless steel, which cracked between 25 to 40 cycles while the least resistant composite, tungsten/Incoloy 907, showed signs of microcracking in less than 10 cycles. The superalloys performed as well as the tungsten/FeCrAl and tungsten/Waspaloy composites.

Low and High-Cycle Fatigue Testing

All low and high-cycle fatigue tests were conducted at 870 °C in a helium atmosphere under tension-tension conditions with a load ratio (minimum stress/maximum stress) of R = 0.2 at 1 and 55 Hz respectively for the low and high-cycle fatigue experiments. The test specimen geometry was the same as that used for tension testing and in all cases specimen fatigue failure was defined as complete separation. Baseline specimens were tested in the as-polished condition. Companion specimens were thermal shock damaged to produce surface microcracks by subjecting the specimens to 55 thermal shock cycles. These samples were also tested to determine the effect of surface condition on cyclic fatigue behavior. The projected upper and lower low-cycle fatigue (strain life) curves for composites reinforced with tungsten-1.5 percent thoria fibers are compared with the experimental data for polished specimens in Fig. 14. The data are within the upper and lower projected bounds except for tungsten/316L stainless steel composites which are more ductile than expected at longer lives. It can be seen that the thermal shock damage to introduce surface microcracks did not have a detrimental effect on the low-cycle fatigue behavior of the composites.

If one makes the assumption that the self imposed stresses in thermal fatigue results in a low-cycle fatigue situation, prediction of life under thermal fatigue behavior can be obtained from the low cyclic test results. For instance, different thermal strains will occur in the blades constructed of different materials when subjected to the same hot gas transient. For a given geometry, the thermal gradients depend on the thermal diffusivity of the material:

$$D_f = K/\rho C$$

where

D_f thermal diffusivity
K thermal conductivity
ρ density
C specific heat

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The temperature gradients for a given configuration subjected to the same thermal transient made of different materials were assumed to be proportional to the reciprocal of their diffusivities, Ref. 1. With MAR M-246 (Hf) (DS) as the baseline, the relative thermal transient strains for the composites are given by:

$$\frac{\Delta\varepsilon \text{ composite}}{\Delta\varepsilon \text{ MAR M-246 (Hf) (DS)}} = \frac{\alpha \text{ composite } (K/\rho C) \text{ MAR M-246 (Hf) (DS)}}{\alpha \text{ MAR M-246 (Hf) (DS) } (K/\rho C \text{ composite})}$$

where

$\Delta\varepsilon$ thermal strain
α thermal expansion

Thus, a thermal strain range of 3 percent for MAR M-246 (Hf) (DS) is reduced to 0.25 percent for a FRS blade because the thermal diffusivity for the composite is almost five times greater than the superalloy, primarly due to the three times higher thermal conductivity. Furthermore the thermal coefficient of expansion of the composite is about 50 percent of that for the superalloy. With the assumption that thermal fatigue can be approximated by low-cycle fatigue testing, the life of a FRS blade subjected to a thermal strain range of 0.35 percent is estimated from Fig. 14 to be 10^4 cycles. This is a significant improvement over the current blade material life of less than 10 cycles.

Figure 15 illustrates the low and high-cycle fatigue data for the tungsten/Waspaloy composite plotted with the stress amplitude as a function of cycles to failure. It can be seen that the attempts to induce thermal shock damage did not have a detrimental effect on the low or high-cycle fatigue strength; both the as-polished data and thermal shock damaged data are in excellent agreement and lie on a single curve which has the form:

$$\Delta\sigma/2 = a(N_f)^b$$

where

$\Delta\sigma$ stress range = maximum stress-minimum stress
$\Delta\sigma/2$ stress amplitude
a constant
N_f cycles to failure
b power law exponent

The fatigue curves for three FRS composites and the two superalloys are plotted in Fig. 16. The curves are for the as-polished and thermal-shock-damaged FRS composites while those for the two superalloys are for the as-polished condition. In the high-cycle fatigue regime, the tungsten/Waspaloy composite showed the highest fatigue strength of the three FRS composites tested and it is higher than that for the superalloys above 10^5 cycles. The fatigue data indicate that the FRS composites can have superior high-cycle fatigue strength retension as the power law exponents are slightly higher than those for conventional wrought superalloys. This further suggests that the fatigue life of the composite is less sensitive to stress amplitude.

Projected high-cycle fatigue (stress life) curves for a Waspaloy matrix composite reinforced with either tungsten-1.5 percent thoria or W-Re-Hf-C fibers are shown in Fig. 17; clearly there is significant benefit to be gained from the use of the higher strength W-Re-Hf-C fiber. The actual fatigue data for tungsten-1.5 percent thoria reinforced Waspaloy composites is also shown in the figure and it lies above the projected curve which indicates that the methodology of estimating fatigue behavior is conservative. Therefore it is anticipated that the fatigue strength of a Waspaloy matrix composite reinforced with W-Re-Hf-C fibers will also be higher than the projection. The W-Re-Hf-C fiber reinforced composite offers a significant advantage for 870 °C high-cycle fatigue conditions compared to the fatigue data for MAR M-246 (Hf) (DS).

Hydrogen Environment Embrittlement Testing

Notched flat sheet tensile specimens were used for hydrogen environment embrittlement tests. The specimens were tension tested in 6.9 MPa hydrogen at room temperature with additional specimens tested in 6.9 MPa helium to provide a basis for comparison for the susceptibility to hydrogen.

As shown in Fig. 18, the tungsten/Incoloy 907, tungsten/316L stainless steel and the tungsten/Waspaloy composites do not appear to have undergone embrittlement in a 6.9 MPa hydrogen environment at room temperature. The fractography showed that the matrices of the three composites all failed in a ductile manner while the fibers broke in a brittle manner. This behavior was identical to that observed after room temperature helium tests. Although additional testing at higher hydrogen pressures must be conducted, the existing data indicate that the FRS composites should perform well in contrast to the behavior of MAR M-246 (Hf) (DS) and single crystal Alloy 1480 (Fig. 18). The FRS composite materials thus offer an advantage over the current SSME blade material relative to use in a hydrogen environment.

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SUMMARY OF RESULTS

Studies were conducted to determine the potential of fiber reinforced superalloys for rocket engine turbine blade use. The first stage blades of the high pressure turbopump of the SSME have been chosen as the reference system, and preliminary design properties were estimated for FRS composite materials based on the use of 50 vol % fiber content W-Re-Hf-C fibers in ductile superalloy matrices. It was concluded based on these projections that FRS turbine blades offer the potential of significantly improved operating life (three orders of magnitude increase over the current material), higher operating temperature capability (over a 200 °C increase) and reduced strains induced by transient thermal conditions during engine start and shut down. In order to develop the FRS composite for use as advanced rocket engine turbine blade material however, a more adequate data base was needed and experimental confirmation of the methodology used to project key design properties for FRS was also required. Research was thus conducted on readily fabricable composites containing 40 vol % tungsten-1.5 percent thoria fibers in several alloy matrices. Experiments were undertaken to evaluate key engineering properties for blade application and to assess the validity of the methodology used in the design property projections. This work yielded the following results:

1. The thermal shock resistance of the FRS composites was excellent, two to nine times better than the current superalloy blade material.

2. The thermal fatigue resistance of the FRS composites was equal to or higher than the current blade material.

3. The tensile and low and high-cycle fatigue strengths were equivalent to greater than the projected properties.

4. Prior thermal shock damage had a negligible influence on the low or high-cycle fatigue behavior of the FRS composites.

5. The FRS composites exhibited negligible embrittlement from a 6.9 MPa hydrogen environment.

6. No ductile brittle transition temperature was observed for FRS materials from -196 to 1100 °C.

Thus the FRS composites have a highly attractive combination of properties for advanced rocket engine turbopump blade application for a temperature range from 870 to 1100 °C. Based on these results continued effort directed towards developing FRS composites for use as rocket turbine blades is underway.

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TABLE I. - COMPARISON OF OPERATING PARAMETERS BETWEEN ROCKET ENGINE TURBINES AND AIRCRAFT GAS TURBINES (REF. 1)

Item	Rocket engine turbines	Aircraft gas turbines
Fuel	Hydrogen or CH_4	Petroleum distillate
Oxidizer	Oxygen	Air
Operating speed, rpm	36 000-110 000	15 000
Blade tip speed, m/s (ft/s)	564 (1850)	564 (1850)
Power/blade, MW (hp)	0.47 (630)	0.15-0.35 (200-470)
Turbine inlet temperature, °C (°F)	870-1205(1600-2200)	1425 (2600)
Heat transfer coefficient, W/m^2 C (Btu/ft^2 h °F)	306 000(54 000)	2840 (500)
Thermal start/stop-transients, °C/S (°F/S)	18 000/2000 (32 000/36000)	56 (100)
Engine starts	55-700	2400
Operational life, hr	7.5-100	8000

TABLE II. - NOMINAL CHEMICAL COMPOSITION OF ALLOYS

Alloy	Element composition, weight percent															
	Ni	Co	Cr	Fe	Mo	Ti	Al	W	Ta	Hf	Nb	Mn	Y	C	B	Zr
MAR M-246 (Hf) (DS)	Bal.	10	9	----	2.5	1.5	5.5	10	1.5	1.75	---	--	-	0.15	-----	----
Alloy 1480 (SC)	Bal.	5.2	9.3	----	0.03	1.4	4.8	4.1	11.8	----	---	--	-	----	-----	----
Waspaloy	Bal.	14	20	----	4	3	1	----	----	----	---	--	-	0.08	0.006	0.06
Incoloy 903	38	15	----	Bal.	----	1.4	0.7	----	----	----	3	--	-	----	-----	----
Incoloy 907	38	13	----		----	1.5	0.03	----	----	----	4.7	--	-	0.02	-----	----
316L Stainless steel	12	----	18		3	---	----	----	----	----	---	2	-	0.03	-----	----
FeCrAl	----	----	24		----	---	4	----	----	----	---	--	-	----	-----	----
FeCrAlY	----	----	24		----	---	4	----	----	----	---	--	1	----	-----	----

TABLE III. - 870 °C ULTIMATE TENSILE STRENGTHS FOR FRS COMPOSITES

Matrix material	Measured ultimate tensile strength for 40 vol % W - 1.5% ThO_2 fibers, MPa	Projected ultimate tensile strength, MPa	
		40 vol % W - 1.5% ThO_2 fibers	50 vol % W-Re-Hf-C fibers
Waspaloy	999	882	1378
316L stainless steel	758	717	1240
Incoloy 907	655	655	1192

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TABLE IV. - THERMAL FATIGUE RESULTS

Material	871 °C peak temperature[a]	1093 °C peak temperature[b]
MAR M-246 (Hf) (DS)	45 to 55	10 to 25
Alloy 1480 (SC)	>55	10 to 25
W/FeCrAl composite	11 to 31	10 to 25
W/907 composite	11 to 31	<10
W/Waspaloy composite	>55	10 to 25
W/316L SS composite	45 to 55	25 to 40

[a]Heated to 871 °C at 220 °C/sec FRS composites required more energy input to achieve this heating rate than the cast superalloys.

[b]Heated to 1093 °C at 220 °C/sec FRS composites required more energy input to achieve this heating rate than the cast superalloys.

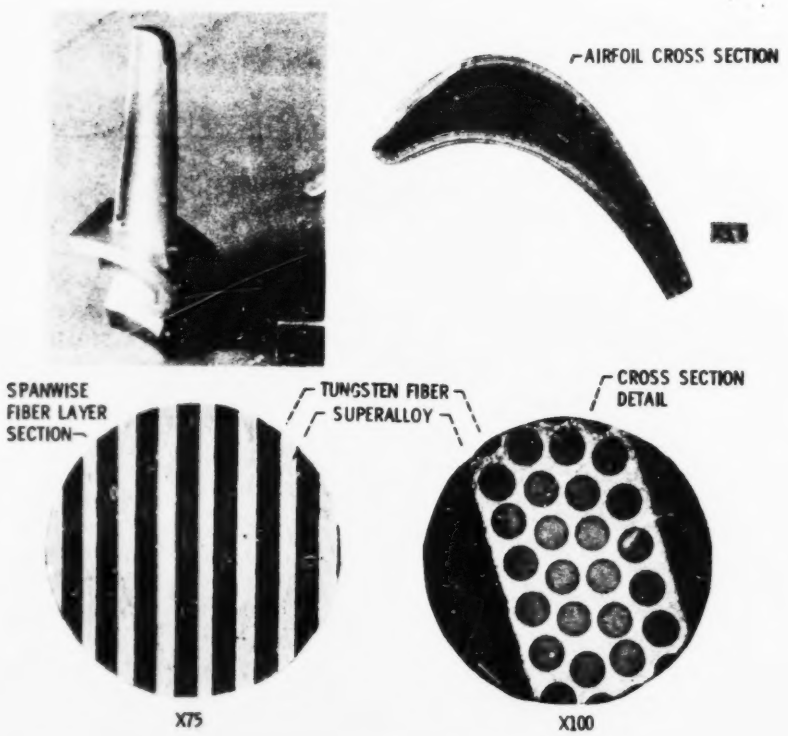

FIGURE 1. - PHOTOGRAPHS AND MICROSTRUCTURE OF A TUNGSTEN FIBER/SUPERALLOY COMPOSITE BLADE. (REF. 5).

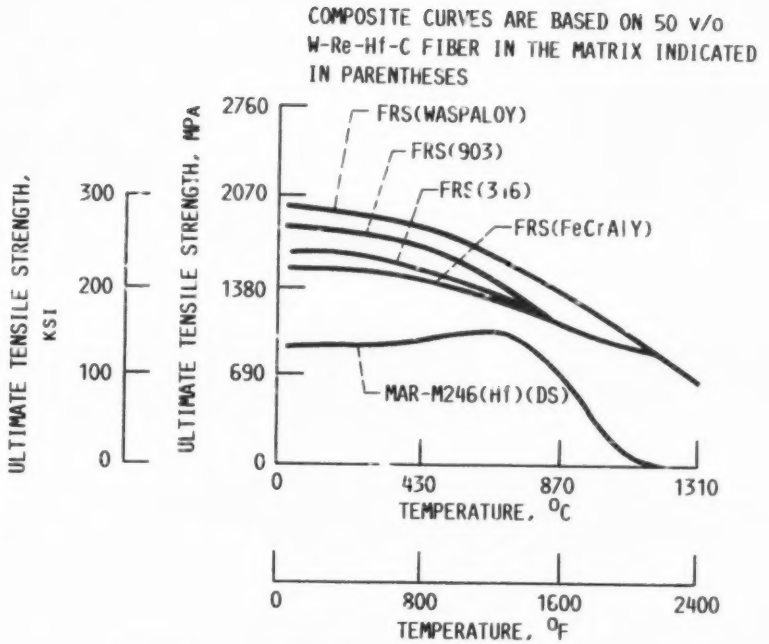

FIGURE 2. - ESTIMATED TENSILE STRENGTH OF CANDIDATE FRS COMPOSITES AS A FUNCTION OF TEMPERATURE COMPARED TO THAT OF MAR-M246 (Hf)(DS). (REF. 6.)

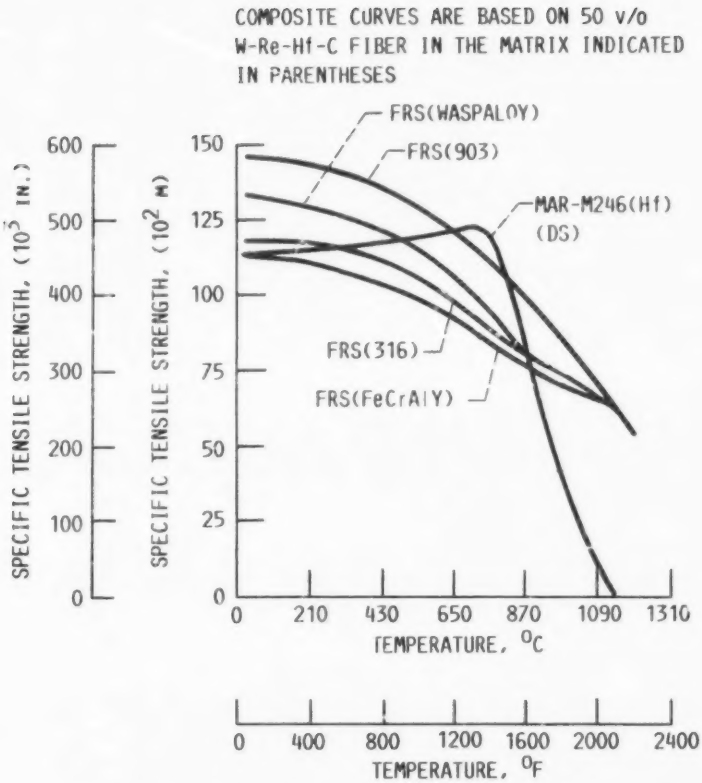

FIGURE 3. - ESTIMATED SPECIFIC STRENGTHS OF CANDIDATE FRS COMPOSITES AS A FUNCTION OF TEMPERATURE COMPARED TO THAT OF MAR-M246(Hf)(DS). (REF. 6.)

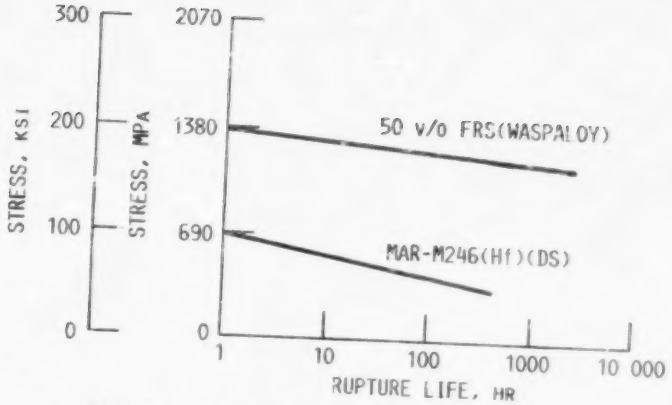

FIGURE 4. - STRESS RUPTURE STRENGTH OF MAR-M246 (Hf)(DS) AND A FRS COMPOSITE AT 870 °C (1600 °F). (REF. 6.)

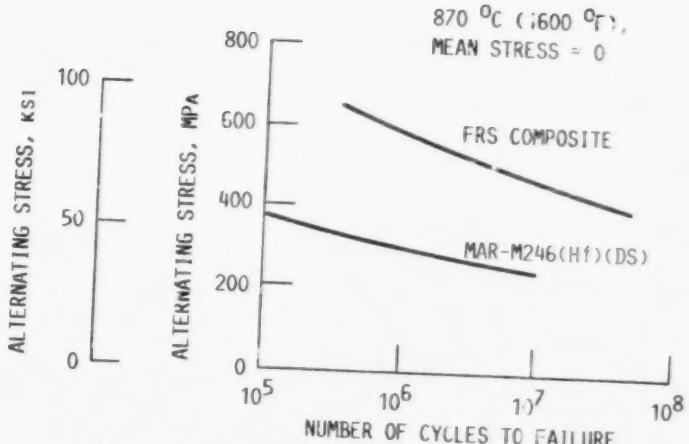

FIGURE 5. - COMPARISON OF THE ESTIMATED HIGH-CYCLE FATIGUE STRENGTH OF A 50 VOL PERCENT W-Re-Hf-C FIBER/WASPALOY COMPOSITE MATERIAL WITH MAR-M246(Hf)(DS). (REF. 1.)

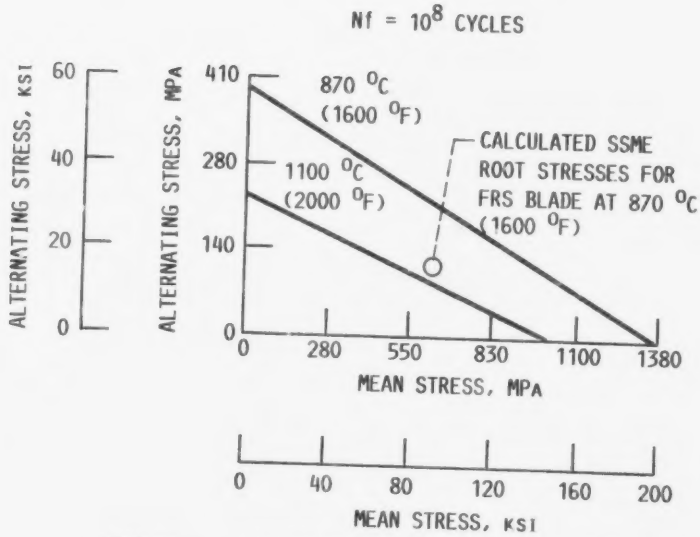

FIGURE 6. - CALCULATED GOODMAN DIAGRAM FOR A W-Re-Hf-C/WASPALOY COMPOSITE. (REF. 6.)

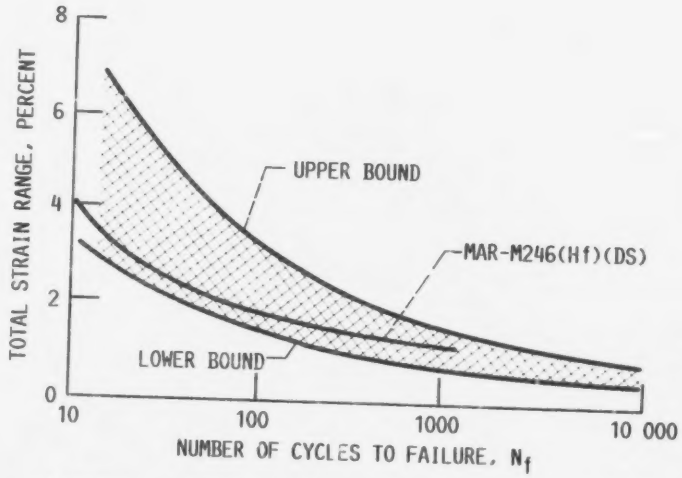

FIGURE 7. - LOW-CYCLE FATIGUE PROJECTION FOR W-Re-Hf-C/WASPALOY COMPOSITE AT 870 °C (1600 °F) COMPARED TO THE BEHAVIOR OF MAR-M246(Hf)(DS). (REF. 6.)

(1) CALCULATED (REF. 3)
(2) MEASURED (REF. 3)
(3) MEASURED (REF. 6)

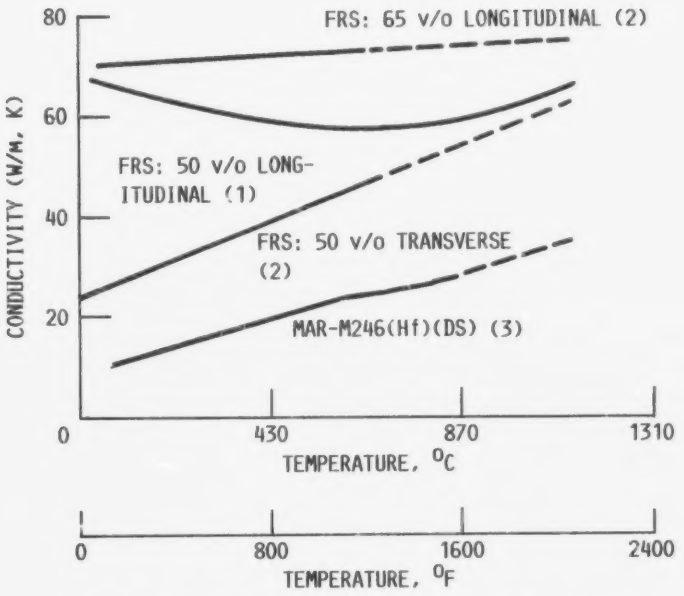

FIGURE 8. - THERMAL CONDUCTIVITY OF A TUNGSTEN FIBER/FeCrAlY COMPOSITE AND MAR-M246(Hf)(DS) AS A FUNCTION OF TEMPERATURE. (REF. 6.)

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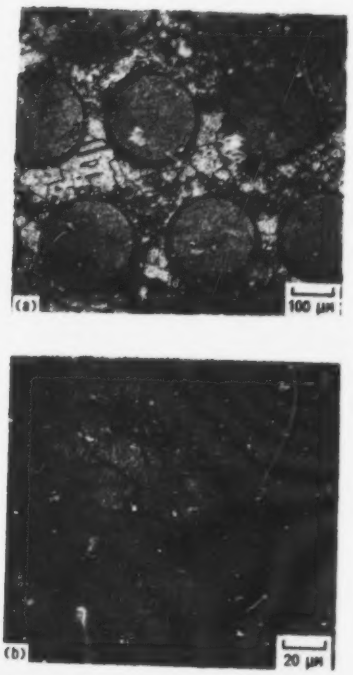

FIGURE 9. - MICROSTRUCTURE OF AN AS-FABRICATED TUNGSTEN-1.5 PERCENT ThO_2/WASPALOY COMPOSITE. (REF. 8.)

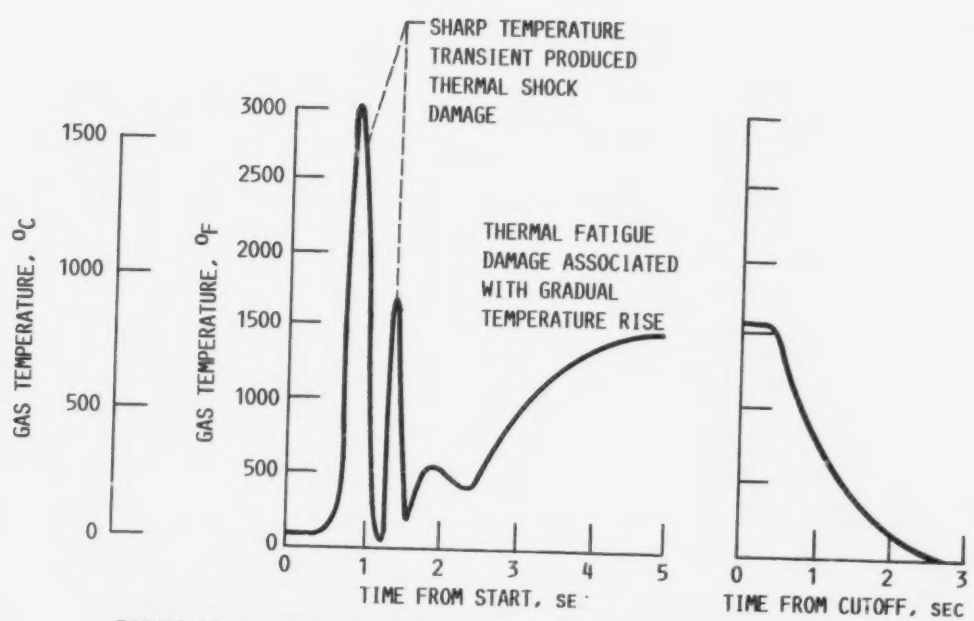

FIGURE 10. - SSME HIGH-PRESSURE FUEL TURBINE INLET TEMPERATURE TRANSIENTS DURING ENGINE START-UP AND SHUTDOWN. (REF. 7.)

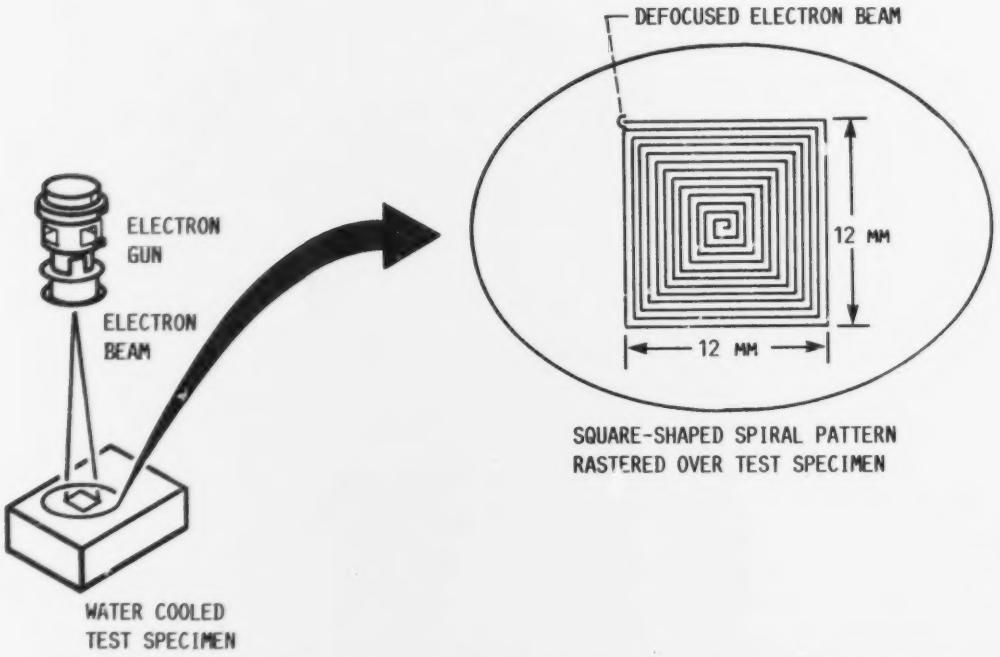

FIGURE 11. - SQUARE-SHAPED SPIRAL PATTERN USED IN THE THERMAL SHOCK AND THERMAL FATIGUE TESTS. (REF. 7.)

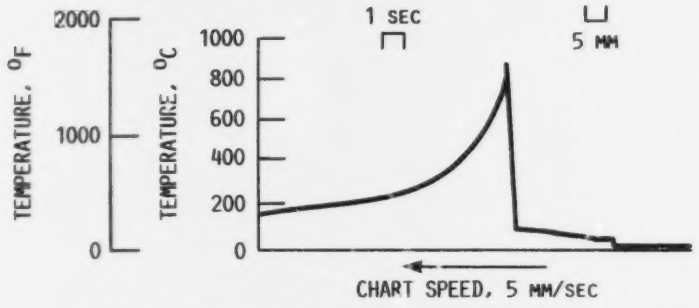

FIGURE 12. - THERMAL SHOCK TEMPERATURE PROFILE SIMULATING THE SSME ENGINE STARTUP TRANSIENT. DURATION OF POWER PULSE IS 0.3 SEC. (REF. 7.)

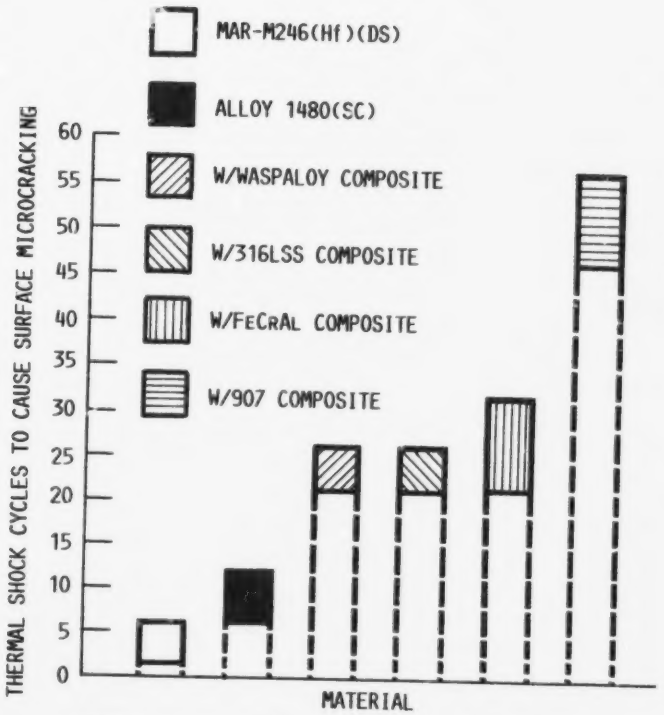

FIGURE 13. - NUMBER OF THERMAL SHOCK CYCLES TO INDUCE SURFACE MICROCRACKING IN FRS COMPOSITES, MAR-M246(Hf)(DS), AND ALLOY 1480 SINGLE CRYSTAL (REF. 8.)

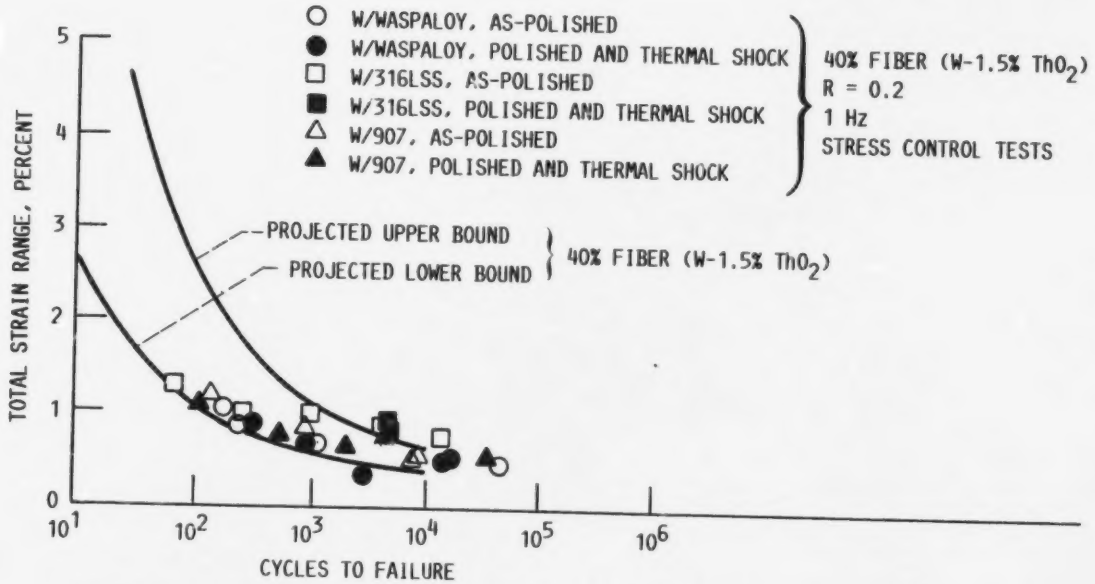

FIGURE 14. - COMPARISON OF 870 °C (1600 °F) ESTIMATED LOW-CYCLE FATIGUE UPPER AND LOWER BOUNDS WITH ACTUAL TEST DATA FOR FRS COMPOSITES. (REF. 8.)

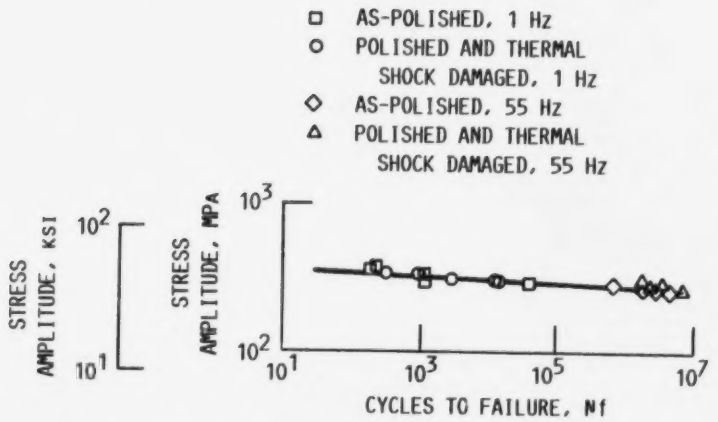

FIGURE 15. - COMBINED LOW AND HIGH-CYCLE FATIGUE DATA FOR A TUNGSTEN-1.5% ThO_2/WASPALOY COMPOSITE TESTED AT 870 ^{o}C (1600 ^{o}F). (REF. 7.)

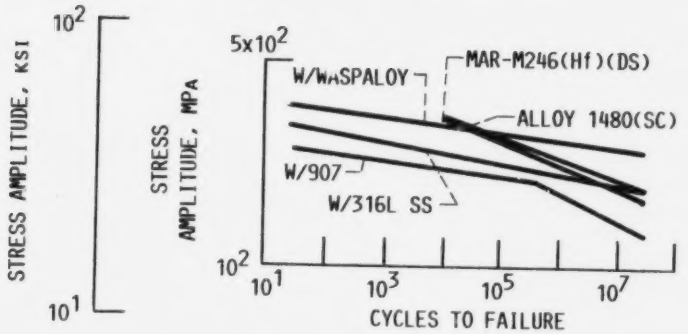

FIGURE 16. - COMPARISON OF THE 870 ^{o}C (1600 ^{o}F) HIGH-CYCLE FATIGUE BEHAVIOR OF SEVERAL FRS COMPOSITES WITH MAR-M246(Hf)(DS) AND SINGLE CRYSTAL ALLOY 1480. (REF. 8.)

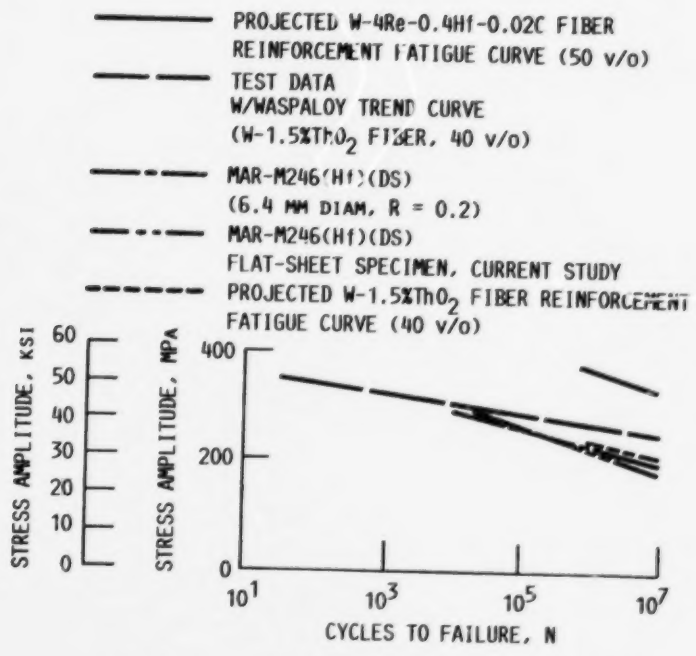

FIGURE 17. - COMPARISON OF THE 870 °C (1600 °F) HIGH-CYCLE FATIGUE DATA FOR A TUNGSTEN/WASPALOY COMPOSITE AND MAR-M246(Hf)(DS) WITH PROJECTED CURVES BASED ON SEVERAL TYPES OF FIBERS AND FIBER CONTENTS. (REF. 8.)

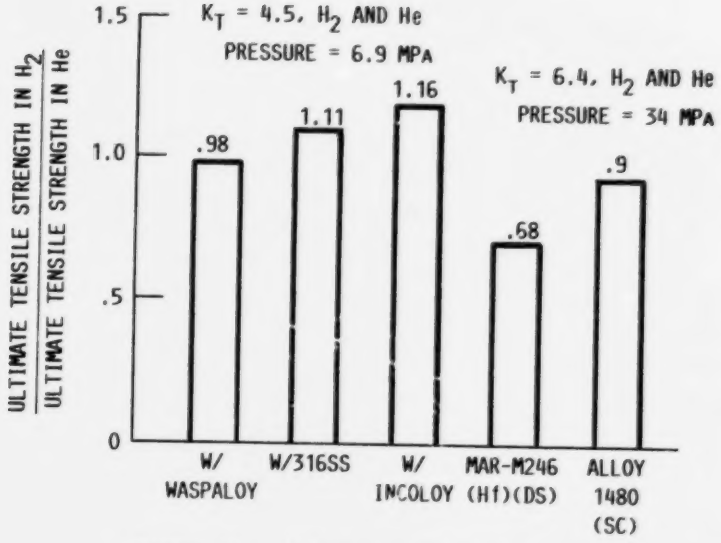

FIGURE 18. - HYDROGEN ENVIRONMENTAL EMBRITTLEMENT RESISTANCE OF FRS COMPOSITES COMPARED TO THAT FOR MAR-M246(Hf)(DS) AND SINGLE CRYSTAL ALLOY 1480. (REF. 8.)

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15. Supplementary Notes

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16. Abstract

High-pressure turbopumps for advanced reusable liquid-propellant rocket engines such as that for the Space Shuttle Main Engine (SSME) require turbine blade materials that operate under extreme conditions of temperature, hydrogen environment, high-cycle fatigue loading, thermal fatigue and thermal shock. Such requirements tax the capabilities of current blade materials. Based on projections of properties for tungsten fiber reinforced superalloy (FRS) composites, it was concluded that FRS turbine blades offer the potential of a several fold increase in life and over a 200 °C increase in temperature capability over the current SSME blade material. FRS composites were evaluated with respect to mechanical property requirements for SSME blade applications. Compared to the current blade material, the thermal shock resistance of FRS materials is excellent, two to nine times better, and their thermal fatigue resistance is equal to or higher than the current blade material. FRS materials had excellent low and high-cycle fatigue strengths, and thermal shock-induced surface microcracks had no influence on their fatigue strength. The material also exhibited negligible embrittlement when exposed to a hydrogen environment.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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